PANIC 05 , Santa Fe, October 25 2005

Minimal Flavor Violation In the Lepton Sector

Vincenzo Cirigliano

Based on Nucl.Phys. B 728 (2005) 121 [hep-ph/0507001]

with Benjamin Grinstein, Gino Isidori and Mark B. Wise

Outline

- Introduction – the “flavor problem”
- Minimal Flavor Violation for Leptons
  - Two formulations: minimal & extended field content
- MLFV phenomenology -- illustrations
- Conclusions

The “Flavor Problem”

- SM: effective theory valid up to cutoff Λ - scale of new d.o.f.

$$\boxed{\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots}$$

- **Solve Hierarchy problem** ➔ **Λ ~ TeV**

FCNC constraints ($c_i^{(d)}=1$) ➔ **Λ > 100 TeV**

The "Flavor Problem"

- SM: effective theory valid up to cutoff Λ - scale of new d.o.f.

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- **Solve Hierarchy problem** ➔ **Λ ~ TeV**

  FCNC constraints ($c_i^{(d)}=1$) ➔ **Λ > 100 TeV**

- NOTE: a "flavor problem" exists in the lepton sector as well

$$\boxed{\mathcal{L} = \frac{e\,\Delta_{\mu e}}{\Lambda^2}\, m_\mu \bar{e}_R \sigma^{\mu\nu} \mu_L F_{\mu\nu}}$$

$$BR(\mu \to e\gamma) < 1.2 \times 10^{-11} \quad ➔ \quad \Lambda > \sqrt{\Delta_{\mu e}} \times 400\ \text{TeV}$$

Evading the "Flavor Problem"

- Λ_F **> 100 TeV** (unnatural, hardly testable)
- Λ **~ TeV + Symmetry Principle** protecting FCNC

$\downarrow$

Minimal Flavor Violation hypothesis

The irreducible sources of flavor symmetry breaking are linked
in a minimal way
to the known structure of fermion (u,d; l,ν) spectra and mixing

- Explicitly built into several model scenarios
- Can be formulated in EFT language
  (not sensitive to model details)

MFV in the quark sector

(straightforward identification of irreducible symmetry breaking sources)

- Symmetry group: $G_{\mathrm{QF}} = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$
- Only irreducible sources of symmetry breaking: SM Yukawa

$$\boxed{\mathcal{L}_{\mathrm{Sym.Br.}} = -\bar{Q}_L^i \, \lambda_D^{ij} \, D_R^j \, H \; - \; \bar{Q}_L^i \, \lambda_U^{ij} \, U_R^j \, (i\tau_2 H) \; + \; \mathrm{h.c.}}$$

Formally invariant under G_{QF} if:

$$\lambda_U \sim (3, \bar{3}, 1)$$

$$\lambda_D \sim (3, 1, \bar{3})$$

MFV in the quark sector

(straightforward identification of irreducible symmetry breaking sources)

- Symmetry group: $G_{\rm QF} = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

- Only irreducible sources of symmetry breaking: SM Yukawa

$$\boxed{\mathcal{L}_{\rm Sym.Br.} = -\bar{Q}^i_L \, \lambda^{ij}_D \, D^j_R \, H \;-\; \bar{Q}^i_L \, \lambda^{ij}_U \, U^j_R \, (i\tau_2 H) \;+\; {\rm h.c.}}$$

Formally invariant under G_{QF} if:

$$\lambda_U \sim (3, \bar{3}, 1)$$
$$\lambda_D \sim (3, 1, \bar{3})$$

- EFT formulation of MFV hypothesis D'Ambrosio et al 2002

> *All effective operators are built out of* ϕ^{SM} ; λ_U, λ_D
> *and are formally invariant under* G_{QF}

Highly predictive framework!

- Examples of dim6 operators in MFV effective Hamiltonian

$$O_{H1} = \bar{Q}_L \gamma^\mu \Delta_{FC} Q_L \, H^\dagger i D_\mu H$$

$$O_{F1} = H^\dagger \, \bar{D}_R \sigma^{\mu\nu} \frac{m_D}{v} \Delta_{FC} Q_L \, F_{\mu\nu}$$

- Effective coupling for $d_i \to d_j$ transitions (V=CKM matrix)

$$\boxed{(\Delta_{FC})_{ij} = (\lambda_U \lambda_U^\dagger)_{ij} \simeq \left(\frac{m_t}{v}\right)^2 V_{3i}^* V_{3j}}$$

Suppression factors (Cabibbo hierarchy)

Involves known masses and mixings → predictions

- Examples of dim6 operators in MFV effective Hamiltonian

$$O_{H1} \quad = \quad \bar{Q}_L \gamma^\mu \Delta_{FC} Q_L \; H^\dagger i D_\mu H$$

$$O_{F1} \quad = \quad H^\dagger \; \bar{D}_R \sigma^{\mu\nu} \frac{m_D}{v} \Delta_{FC} Q_L \; F_{\mu\nu}$$

- Effective coupling for $d_i \to d_j$ transitions (V=CKM matrix)

$$\boxed{(\Delta_{FC})_{ij} = (\lambda_U \lambda_U^\dagger)_{ij} \simeq \left(\frac{m_t}{v}\right)^2 V_{3i}^* V_{3j}}$$

Suppression factors (Cabibbo hierarchy)

Involves known masses and mixings → predictions

- If neutrinos are Dirac same analysis applies to leptons → charged LFV coupling ~ $(m_\nu / v)^2$ -- not very interesting!

MFV in the lepton sector

(identification of symmetry and sources of breaking not straightforward)

- Assume that LN is broken at (high) scale $\Lambda_{\rm LN}$ → naturally small ν masses
- Identify lepton-flavor breaking structures accounting for observed masses and mixing (bottom-up approach):

Dim 4 Yukawa

$$\boxed{\lambda_E = \frac{m_\ell}{v}}$$

Dim 5 |ΔL|=2 Weinberg $\mathcal{L} = g_\nu \frac{(LH)(HL)}{\Lambda_{\rm LN}}$

$$\boxed{g_\nu = \frac{\Lambda_{\rm LN}}{v^2} \hat{U}^* m_\nu^{\rm diag} \hat{U}^\dagger}$$

Irreducible

Reducible
(e.g. see-saw with heavy ν_R)

$$\sim \lambda_\nu^T \lambda_\nu$$

MLFV: minimal field content

- Breaking of $U(1)_{LN}$ and G_{LF} are independent ($\Lambda_{LN} >> \Lambda_{LFV}$)
- $G_{\rm LF} = SU(3)_{L_L} \times SU(3)_{E_R}$ broken only by λ_e , g_ν

$$\boxed{\mathcal{L}_{\rm Sym.Br.} = -\lambda_e^{ij} \bar{e}_R^i (H^\dagger L_L^j) - \frac{1}{2\Lambda_{\rm LN}} g_\nu^{ij} (\bar{L}_L^{ci} \tau_2 H)(H^T \tau_2 L_L^j) + {\rm h.c.}}$$

Formally invariant under $\boxed{\begin{array}{l} L_L \to V_L L_L \\ e_R \to V_R e_R \end{array}}$ if $\boxed{\begin{array}{l} \lambda_e \to V_R \lambda_e V_L^\dagger \\ g_\nu \to V_L^* \, g_\nu V_L^\dagger \end{array}}$

MLFV: minimal field content

- Breaking of $U(1)_{LN}$ and G_{LF} are independent ($\Lambda_{LN} >> \Lambda_{LFV}$)

- $G_{\rm LF} = SU(3)_{L_L} \times SU(3)_{E_R}$ broken only by λ_e , g_ν

$$\boxed{\mathcal{L}_{\rm Sym.Br.} = -\lambda_e^{ij}\bar{e}_R^i(H^\dagger L_L^j) - \frac{1}{2\Lambda_{\rm LN}} g_\nu^{ij}(\bar{L}_L^{ci}\tau_2 H)(H^T\tau_2 L_L^j) + \text{h.c.}}$$

Formally invariant under $\boxed{\begin{array}{l} L_L \to V_L L_L \\ e_R \to V_R e_R \end{array}}$ if $\boxed{\begin{array}{l} \lambda_e \to V_R \lambda_e V_L^\dagger \\ g_\nu \to V_L^* \, g_\nu V_L^\dagger \end{array}}$

- EFT formulation of MLFV hypothesis:

> *All effective operators are built out of* ϕ^{SM} ; λ_e , g_ν
> *and are formally invariant under* G_{LF} *and* $U(1)_{LN}$

MLFV: extended field content

- ν_R mass term $\nu_R^{T\,i}\, C\, \left(M_\nu \delta^{ij}\right)\, \nu_R^j$
  - U(1)$_{LN}$ breaking @ $M_\nu \gg \Lambda_{LFV}$
  - $SU(3)_{\nu_R} \to O(3)_{\nu_R}$

- $\bar{G}_{\rm LF} = SU(3)_{L_L} \times SU(3)_{E_R} \times O(3)_{\nu_R}$ broken only by $\lambda_e\ ,\ \lambda_\nu$

$$\boxed{\mathcal{L}_{\rm Sym.Br.} = -\lambda_e^{ij}\bar{e}_R^i (H^\dagger L_L^j) + i\lambda_\nu^{ij}\bar{\nu}_R^i (H^T \tau_2 L_L^j) + {\rm h.c.}}$$

Formally invariant under $\boxed{\begin{array}{l} L_L \to V_L\, L_L \\ e_R \to V_R\, e_R \\ \nu_R \to O_\nu\, \nu_R \end{array}}$ if $\boxed{\begin{array}{l} \lambda_e \to V_R\, \lambda_e V_L^\dagger \\ \lambda_\nu \to O_\nu\, \lambda_\nu V_L^\dagger \end{array}}$

- EFT formulation:

All effective operators are built out of ϕ^{SM} ; $\lambda_e\ ,\ \lambda_\nu$
and are formally invariant under $\overline{G}_{LF}$ *and* $U(1)_{LN}$

MLFV effective Lagrangian

- At $E < \Lambda_{LFV}$ (new d.o.f.) $\ll \Lambda_{LN}$

$$\boxed{\mathcal{L} = \frac{1}{\Lambda_{\rm LFV}^2} \sum_{i=1}^{5} c_{LL}^{(i)} O_{LL}^{(i)} + \frac{1}{\Lambda_{\rm LFV}^2} \left(\sum_{j=1}^{2} c_{RL}^{(j)} O_{RL}^{(j)} + \text{h.c.} \right)}$$

- Basis for dim 6 operators contributing to $\ell_i \to \ell_j$

$$\begin{aligned}
O_{LL}^{(1)} &= \bar{L}_L \gamma^\mu \Delta L_L \; H^\dagger i D_\mu H \\
O_{LL}^{(2)} &= \bar{L}_L \gamma^\mu \tau^a \Delta L_L \; H^\dagger \tau^a i D_\mu H \\
O_{LL}^{(3)} &= \bar{L}_L \gamma^\mu \Delta L_L \; \bar{Q}_L \gamma_\mu Q_L \\
O_{LL}^{(4d)} &= \bar{L}_L \gamma^\mu \Delta L_L \; \bar{d}_R \gamma_\mu d_R \\
O_{LL}^{(4u)} &= \bar{L}_L \gamma^\mu \Delta L_L \; \bar{u}_R \gamma_\mu u_R \\
O_{LL}^{(5)} &= \bar{L}_L \gamma^\mu \tau^a \Delta L_L \; \bar{Q}_L \gamma_\mu \tau^a Q_L
\end{aligned}$$

$$\begin{aligned}
O_{RL}^{(1)} &= g' H^\dagger \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, B_{\mu\nu} \\
O_{RL}^{(2)} &= g H^\dagger \bar{e}_R \sigma^{\mu\nu} \tau^a \lambda_e \Delta L_L \, W_{\mu\nu}^a \\
O_{RL}^{(3)} &= (D_\mu H)^\dagger \bar{e}_R \lambda_e \Delta D_\mu L_L \\
O_{RL}^{(4)} &= \bar{e}_R \lambda_e \Delta L_L \; \bar{Q}_L \lambda_D d_R \\
O_{RL}^{(5)} &= \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \; \bar{Q}_L \sigma_{\mu\nu} \lambda_D d_R \\
O_{RL}^{(6)} &= \bar{e}_R \lambda_e \Delta L_L \; \bar{u}_R \lambda_U^\dagger i \tau^2 Q_L \\
O_{RL}^{(7)} &= \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \; \bar{u}_R \sigma_{\mu\nu} \lambda_U^\dagger i \tau^2 Q_L
\end{aligned}$$

- Effective coupling governing $\ell_i \longrightarrow \ell_j$ transitions

$$\boxed{\Delta\big|_{\mathrm{minimal}} = g_\nu^\dagger g_\nu = \frac{\Lambda_{\mathrm{LN}}^2}{v^4}\,\hat{U} m_\nu^2 \hat{U}^\dagger}$$

PMNS matrix

\- FCNC suppression ←→ “smallness” of $g_\nu \sim (\Lambda_{\mathrm{LN}} / v^2)\ m_\nu$

$\Lambda_{\mathrm{LFV}} \sim 1$ TeV → suppression is effective for $\Lambda_{\mathrm{LN}} < 10^{13}$ GeV

(This works quite differently from quark case!)

- Effective coupling governing $\ell_i \rightarrow \ell_j$ transitions

$$\boxed{\Delta\big|_{\rm minimal} = g_\nu^\dagger g_\nu = \frac{\Lambda_{\rm LN}^2}{v^4}\,\hat{U} m_\nu^2 \hat{U}^\dagger}$$

PMNS matrix

- FCNC suppression ←→ "smallness" of $g_\nu \sim (\Lambda_{LN} / v^2)\ m_\nu$

$\Lambda_{LFV} \sim 1$ TeV → suppression is effective for $\Lambda_{LN} < 10^{13}$ GeV

(This works quite differently from quark case!)

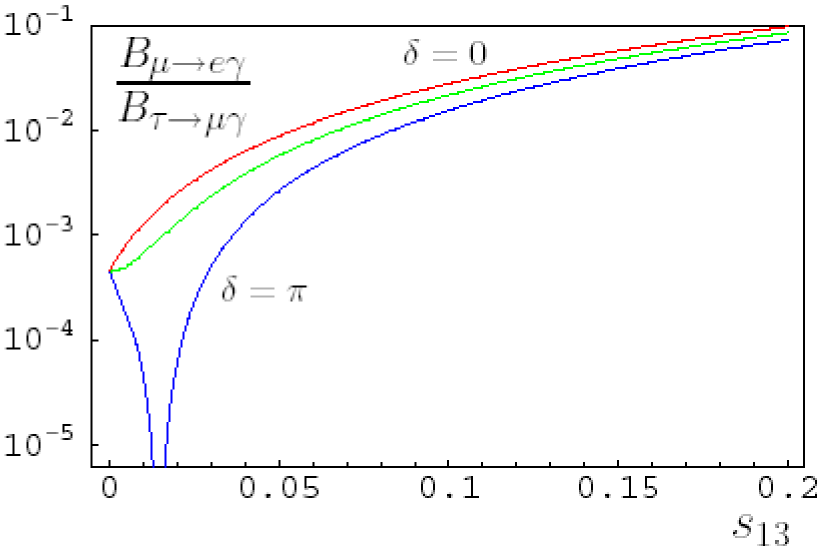
- Predictive power → linking ν phenomenology and (L)FCNC:

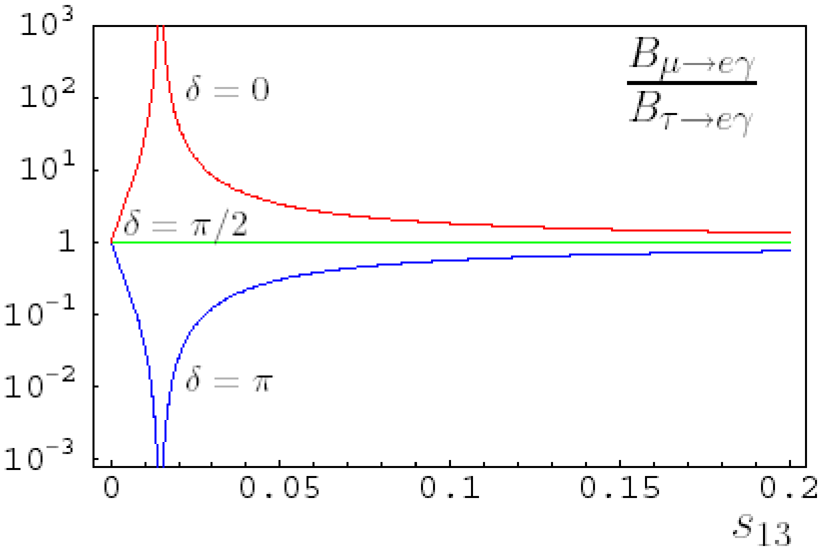
$$\begin{aligned}
\Delta_{\mu e} &= \frac{\Lambda_{\rm LN}^2}{v^4}\,\frac{1}{\sqrt{2}}\left(s\,c\,\Delta m^2_{\rm sol} \pm s_{13}\,e^{i\delta}\,\Delta m^2_{\rm atm}\right) \\
\Delta_{\tau\mu} &= \frac{\Lambda_{\rm LN}^2}{v^4}\,\frac{1}{2}\left(-c^2\,\Delta m^2_{\rm sol} \pm \Delta m^2_{\rm atm}\right)
\end{aligned}$$

Example of MLFV predictions

(in minimal field content)

- Ratios of $B_{l_i \to l_j \gamma}$ (c^(l) and scales Λ cancel out)





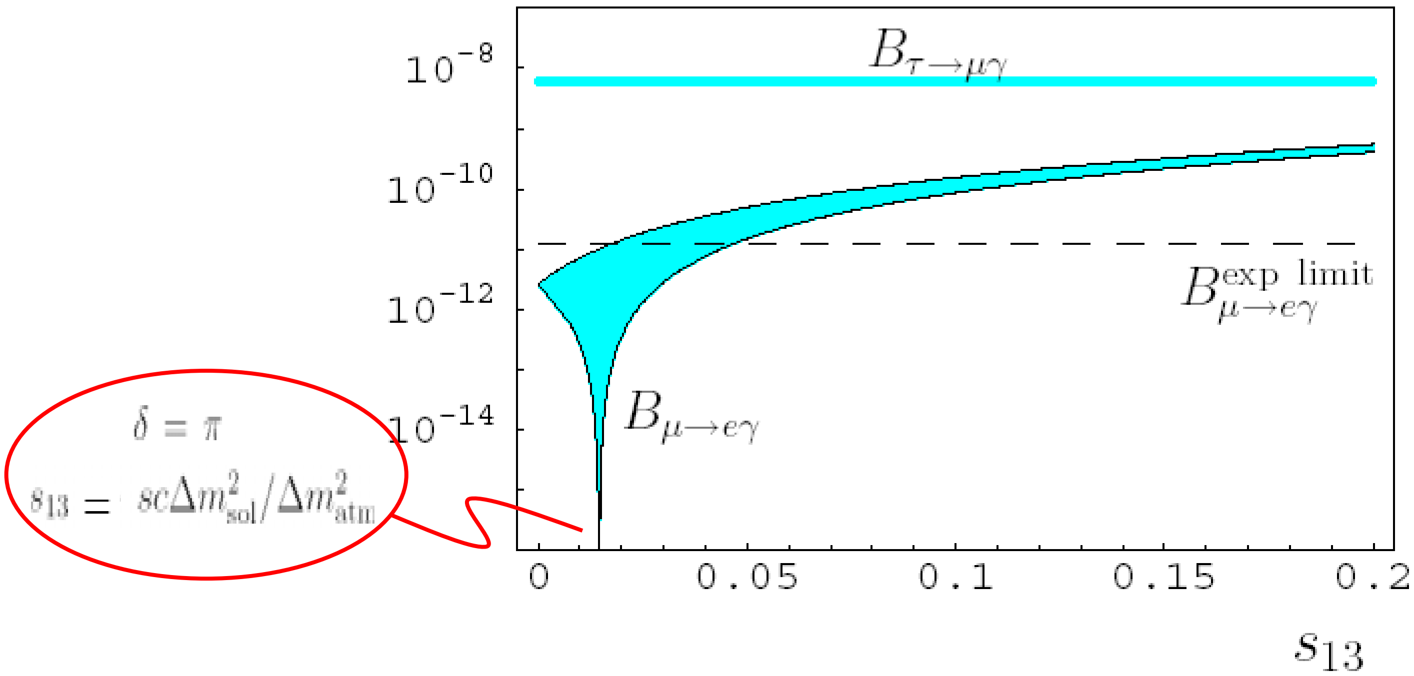
NOTE: plots are for normal hierarchy [inverted is obtained by $\delta \to \pi - \delta$]

(a) Clear pattern: $B_{\tau\to\mu\gamma} \gg B_{\tau\to e\gamma} \sim B_{\mu\to e\gamma}$

(with $\mu\to e/\tau\to\mu$ suppression increasing as $s_{13} \to 0$)

(b) Interesting feature: window for $\tau \to \mu\, \gamma$

$$\Lambda_{\rm LN}/\Lambda_{\rm LFV} = 10^{10} \qquad c_{RL}^{(2)} - c_{RL}^{(1)} = 1$$



→ Can keep $B_{\mu\to e\gamma}$ below expt. limit
while $BR(\tau \to \mu\gamma) > 10^{-9}$, within reach of (super)-B factories

→ Can be easily falsified as we learn more about s_{13}, δ

Conclusions

- Minimal Flavor Violation hypothesis in the lepton sector

  Symmetry principle + EFT

- We have identified two MLFV scenarios where

  - FCNC suppression ←→ 'smallness' of Λ_{LN} ($\Lambda_{LN} < 10^{13}$ GeV)
  - Predictions for relative strength of $\mu \to e$, $\tau \to \mu$, $\tau \to e$ in terms of ν mixing and mass pattern
  - $\tau \to \mu\gamma$ observable at (super)-B factories if $\mathbf{s_{13} \leq 0.1}$

- In progress: 4-lepton processes, viability of leptogenesis